CURRENT TOPICS ON INTERANNUAL VARIABILITY OF THE ASIAN MONSOON

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1. Introduction

This paper highlights current research topics of the interannual variability (IAV) of the Asian summer monsoon. Its purpose is to provide focus, and simulate discussions during the IWM-III workshop. An extended bibliography is provided for further readings and reference.

2. Characterizing Monsoon IAV

Despite over a century of research, characterizing monsoon IAV still remains a vexing problem. This is because the Asian monsoon encompasses complex, multi-scale variability from days to decades, with spatial scales from a few kilometers to thousands of kilometers. As a result, regional descriptions are not always compatible among themselves and with the large-scale perspective. Notwithstanding this obvious difficulty, monsoon indices have been used commonly to provide a simple and quick characterization of the monsoon. An analogy is the use of the Dow Jones Index to describe the state of the US financial market – useful, but far from perfect, as a benchmark reference. Perhaps the most widely used monsoon index is the AIMR, computed as the anomalous rainfall over whole India averaged from June to September (Parthasarathy *et al.* 1992; Mooley and Parthasarathy 1984). Recently, various monsoon indices have been constructed based on dynamical characteristics of dominant modes of the Asian monsoon (e.g., Wang and Fan 1999; Lau *et al*. 2000, Li and Zeng 2003). Table 1 shows several commonly-used monsoon indices including their definitions and applications. They include the all-India monsoon rainfall (AIMR) index, the Webster and Yang (W-Y) monsoon index, the regional monsoon index for South Asia (RM1), the regional monsoon index for East Asia (RM2), and a monsoon index for Southeast Asia (DU2).

Figure 1 shows the regression patterns of 850-mb winds against different monsoon indices. The main feature associated with the W-Y index is a zonally-elongated band of westerlies stretching from eastern Africa to the Philippines (Fig. 1a). The westerlies converge with easterlies from the western Pacific over a zone of increased rainfall over the maritime continent. Also found are several other convergence centers associated with the cyclonic circulation over northern Bay of Bengal and the South China Sea. W-Y measures the broad-scale monsoon circulation, contributed collectively by various regional components. In contrast, RM1 captures the westerly from the Arabian Sea to western Bay of

Bengal, with strong cross-equatorial flow and meridional component of wind over the Bay of Bengal (Fig. 1b). A key difference compared to W-Y is that in RM1, the tropical easterly extends further westward, covering the entire Southeast Asia. Both RM2 and DU2 depict variations of the East Asian monsoon. RM2 shows alternating easterlies and westerlies from the equatorial regions to the extratropics (0º-50ºN) in the longitude sector of 110º-140ºE, consistent with multiple meridional cell structure of the East Asia monsoon, which is closely related to the north-south shift of overlying jet stream. Compared to others, DU2 (Fig. 2d) tends to emphasizes tropical features over Southeast Asia and western Pacific. It also shows a strong signal in the southern portion of the subtropical western Pacific high. As in WY and in RM1, DU2 captures an east-west dipole rainfall anomaly between the Indian Ocean and the western Pacific. Users of specific monsoon index need to recognize the dynamical consistency and the main emphases of that index with respect to other indices, and to the dominant mode of monsoon IAV.

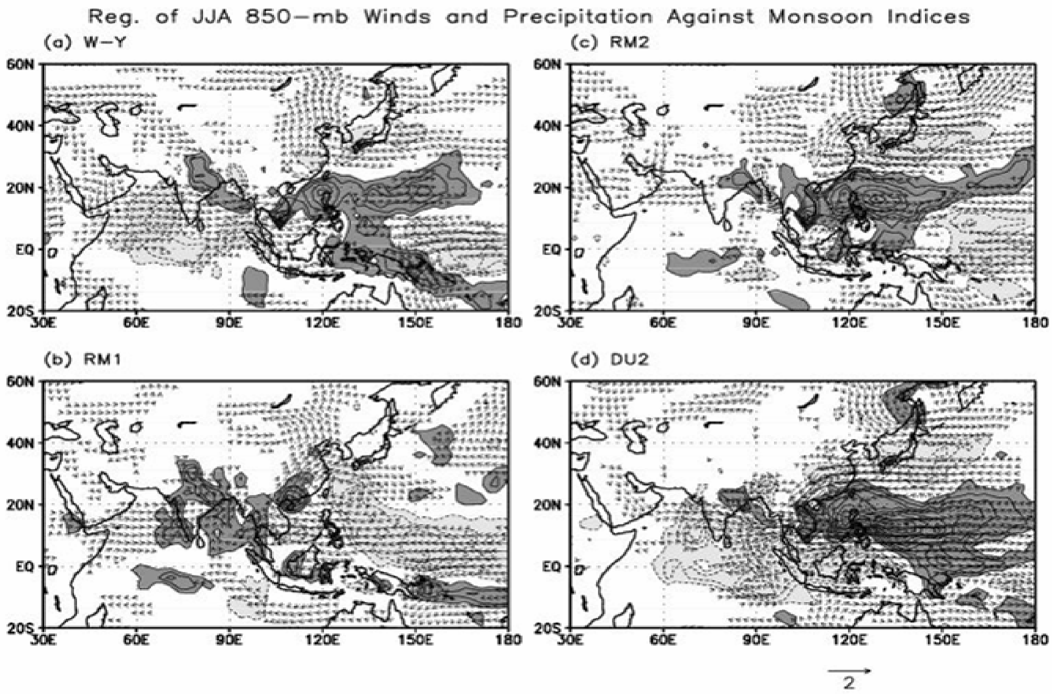

Fig. 1. Patterns of regression analysis of JJA 850-mb winds (vectors in ms^{-1}) and precipitation (contours in mm day $^{-1}$) against various monsoon indices shown in Table 1, for the period 1949-2003. Contour interval is 0.3 and the zero contour is omitted. Values larger than 0.3 are shaded heavily; less than -0.3 are shaded lightly.

Table 1. Commonly-applied monsoon indices of the Asian summer monsoon

Name of Index	**Type of Index**	**Domain of Application**	**Definition**	**Reference**
AIMR	Precipitation	India	Rainfall over India	Parthasarathy *et al.* (1992)
W-Y	Circulation	Tropical Asia	U850-U200 Over 0º-20ºN, 40º-110ºE	Webster and Yang (1992)
RM1	Circulation	South Asia	V850-V200 Over 10º-30ºN, 70º-110ºE	Goswami *et al.* (1999)
DU2	Circulation	Southeast Asia	U850 (5º-15ºN, 90º-130ºE) - U850 (22.5º-32.5ºN, 110º-140ºE)	Wang and Fan (1999)
RM2	Circulation	East Asia	U200 (40º-50ºN, 110º-150ºE) - U200 (25º-35ºN, 110º-150ºE)	Lau *et al.* (2000)

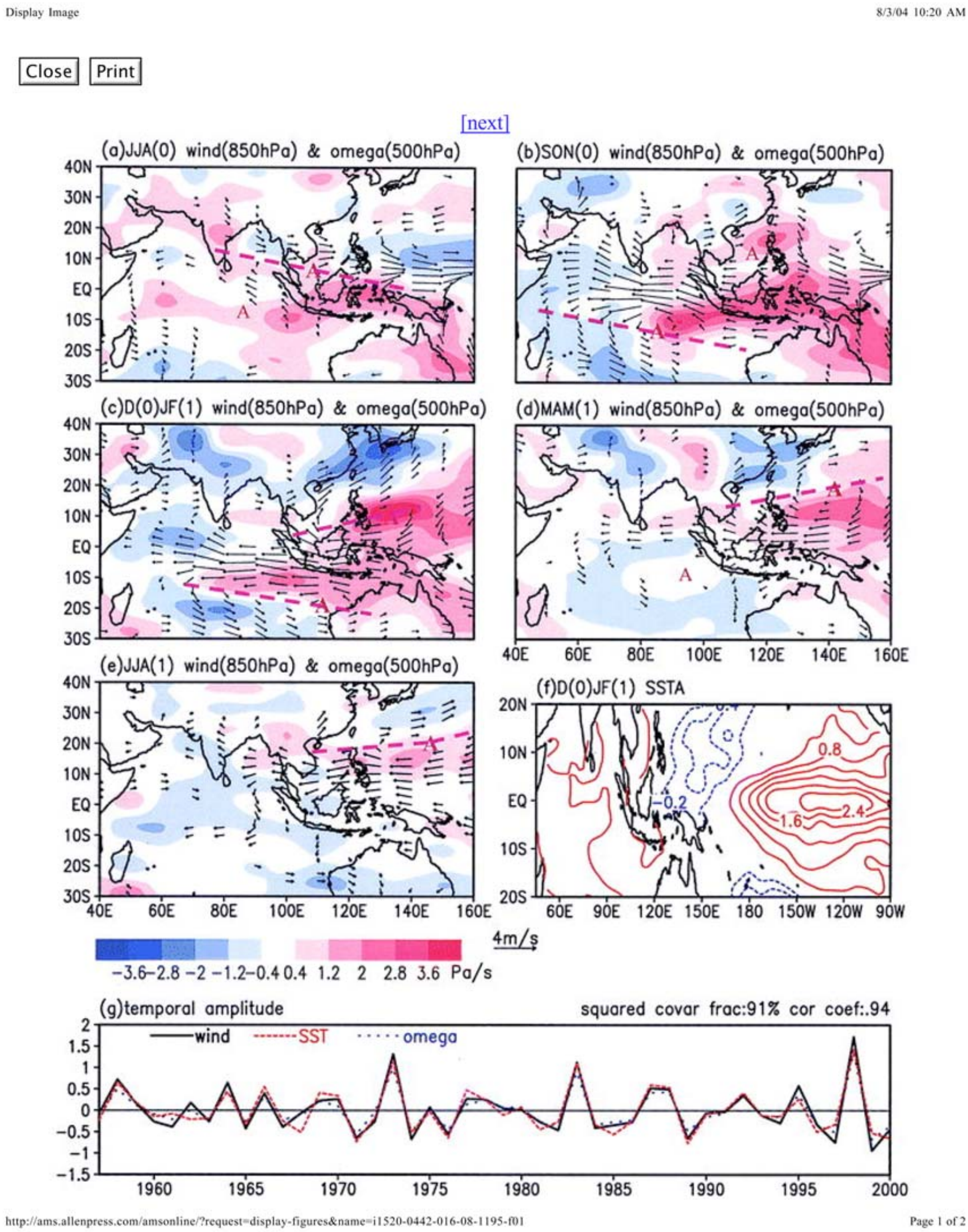

Fig. 2. Spatial patterns of principal modes (a-f) and time coefficients (g) of wind and SST anomalies. In panels (a-e), vectors represent 850-mb horizontal winds (only values with significance higher than 95% confidence level are shown) and shadings show 500-mb vertical motions. Year 0 denotes the year when El Niño develops. (From Wang *et al.* 2003)

3. Monsoon-ENSO Relationships

The most dominant mode of IAV of the Asian summer monsoon is that arising as a response to the basin-scale SST anomalies during ENSO. Fig. 2 shows the evolution of anomalous atmospheric circulation and vertical motion field (color contour) associated with the first principal component of the monsoon IAV over the South Indian Ocean and western North Pacific. The D(0)JF(1) marker refers to the time of maximum SST anomaly over the tropical eastern Pacific (Fig. 1f). The most pronounced feature is the waxing and waning of two large-scale anticyclones over the eastern Indian Ocean and the western Pacific. The development of the South Indian Ocean anticyclone is most pronounced in the fall and the western North Pacific anticyclone in the winter. The sinking motion is well established in the western Pacific during D(0)JF(1), with anomalous over East Asia. At JJA(0), the summer before the peak of eastern tropical SST, moderate sinking motion are found over the maritime continent and the Indian subcontinent indicating a general suppression of the Indian monsoon. Comparing the JJA(0) and JJA(1), a strong biennial tendency, in which monsoon anomalies reverse from one summer to the next, is noted especially over the western North Pacific, the maritime continent, and the northern Indian Ocean.

While ENSO clearly has an impact on IAV of the Asian monsoon, exactly how they occur remained unknown. There are cases of strong ENSO, having little or no impact on the Indian monsoon, and there are years in which monsoon droughts and floods occur without strong ENSO. The complexity of the ENSO-monsoon relationship is illustrated by the diverse correlations between El Nino SST anomaly and the monsoon indices. The AIRM is significantly correlated with ENSO in summer and the following fall to winter. On the other hand, W-Y has significant correlation in boreal spring through the fall, mainly because W-Y is affected strongly by the western Pacific wind. All the other regional monsoon indices, RM1, DU2 and RM2 show very little correlations with ENSO. However, these do not preclude in individual ENSO events, when regional features described by these indices are strongly affected by ENSO. Similarly recent studies have indicated that during the last two decades, the relationship between AIRM and ENSO has weakened considerable compared to previous decades (Krishnamurty *et al*. 2001)

Table 2. Correlation between various summer monsoon indices and NINO3.4 SST of different lags (1950-2003; 1950-2000 for AIMR). Correlations exceeding the 95% confidence level are indicated in bold.

	DJF-	**MAM-**	**JJA0**	**SON+**	**DJF+**
AIMR	0.17	-0.09	**-0.50**	**-0.52**	**-0.46**
W-Y	-0.14	**-0.41**	**-0.46**	**-0.42**	-0.34
RM1	0.06	-0.13	-0.31	-0.38	-0.33
DU2	-0.42	-0.24	0.27	0.38	0.36
RM2	-0.13	-0.17	-0.08	-0.08	-0.15

GCM experiments have had reasonable success in simulating the large scale aspects of monsoon ENSO interaction (Soman and Slingo 1997, Slingo and Annamalai 2000). Diagnosis of output from atmospheric general circulation model (AGCM) experiments performed at various research centers indicates that the current generation of models is capable of reproducing the anomalous anticyclones over the Indian Ocean and western North Pacific during warm ENSO years (e.g., Lau and Nath 2000). The impact of these circulation features on the precipitation and temperature patterns in various sectors of the Asia/Australian monsoon region has also been simulated. The model results suggest that the anticyclones are primarily Rossby-wave responses to anomalous heat sinks over Indonesia and the equatorial western Pacific. Such diabatic cooling is in turn caused by the eastward displacement of the rising branch of the Walker Circulation during warm ENSO events. These inferences drawn from the AGCM experiments have been verified by the solutions of mechanistic stationary wave models subjected to diabatic forcing prescribed in the tropical western Pacific (Wang *et al.* 2003, Lau *et al.* 2004).

4. Regional SST

The SSTs in the western Pacific and Indian Oceans and other coastal water domains are important for the Asian monsoon. Although the variability of regional SST is not necessarily always independent from ENSO, there is evidence that to a large extent regional SST in the Indian Ocean and the far western Pacific may vary independently from that in the tropical central-eastern Pacific. Lau and Wu (2001) showed that in some regional SST in the western Pacific and Indian Ocean can explain up to 20% of the IAV variance of the Asian monsoon. However, local SST's usually exhibits complex variability. Some local SST anomalies may represent passive response to atmospheric forcing and not necessarily a forcing to the monsoon. This has caused much difficulty in unraveling causal relationships between the Asian monsoon and the regional.

Regional SST influences the Asian monsoon through exchanges in surface fluxes of heat and momentum, causing contrasts in temperature and convective potential between land and oceans. A rise in SST enhances evaporation and thus moisture supply and latent heating in the atmosphere. As a result, monsoon rainfall increases. On the other hand, warming in oceans reduces the summertime land-sea thermal contrast and the lead to a weakening of the monsoon circulation. Recent studies have suggested that the tropical Indian Ocean SST dipole or the Indian Ocean Zonal Mode (IOZM) is important in controlling the Asian summer monsoon (Saji *et al.* 1999; Webster *et al.* 1999). The question of whether the IOZM is dependent on ENSO or an intrinsic mode of the Indian Ocean is still a subject of debate. The presence of the IOZM has been confirmed in many coupled models. Fig. 3 shows the evolution of the IOZM in the UCLA coupled model (Yu and Lau 2004). The dipole mode grows fast in summer and reaches maximum amplitude (warm mature stage) in the fall, as wind- generated oceanic Rossby wave modes. Studies also indicate that the IOZM may be excited from stochastic forcing of the Indian Ocean by Asian monsoon winds (Li *et al.* 2003, Yu and Lau, 2004). Other studies have pointed out that the zonal dipole mode may not be the most dominant mode of the Indian Ocean and that the maximum variance of the SST is in the southern subtropics and extratropics.

A number of observed characteristics of the IOZM have also been simulated in a 900-year experiment with a coupled GCM at GFDL (Lau and Nath 2004). It is seen that from this model study that a substantial fraction of the simulated episodes with IOZM-like behavior is closely linked to ENSO. However, there also exist in this experiment considerable number of cases with pronounced IOZM signals, but with no noticeable ENSO development in the tropical Pacific. The latter events are associated with a hemisphere-wide seal level pressure pattern bearing some resemblance to the Antarctic Oscillation. These model results suggest that the IOZM may be attributable to multiple factors, including remote influences due to ENSO and extratropical changes.

Model experiments have been performed by allowing the simulated ENSO responses in the atmosphere to influence the oceanic surface conditions in the Indo-western Pacific sector through anomalous heat and radiative fluxes at the air-sea interface (Lau and Nath 2003; Lau *et al.* 2004). These model studies demonstrate that many regional SST anomalies observed in the Indian

Ocean basin as well as the marginal seas off East Asia and eastern Australia during certain phases of the ENSO cycle are caused by the effects of these `atmospheric bridges' on the underlying oceanic mixed layer. Analyses of the two-way air-sea interactions in such coupled model experiments further indicate that the SST anomalies generated by the bridge mechanism could in turn feedback on the atmospheric circulation, and thereby influence the circulation and precipitation in many parts of the Asian-Australian monsoon system.

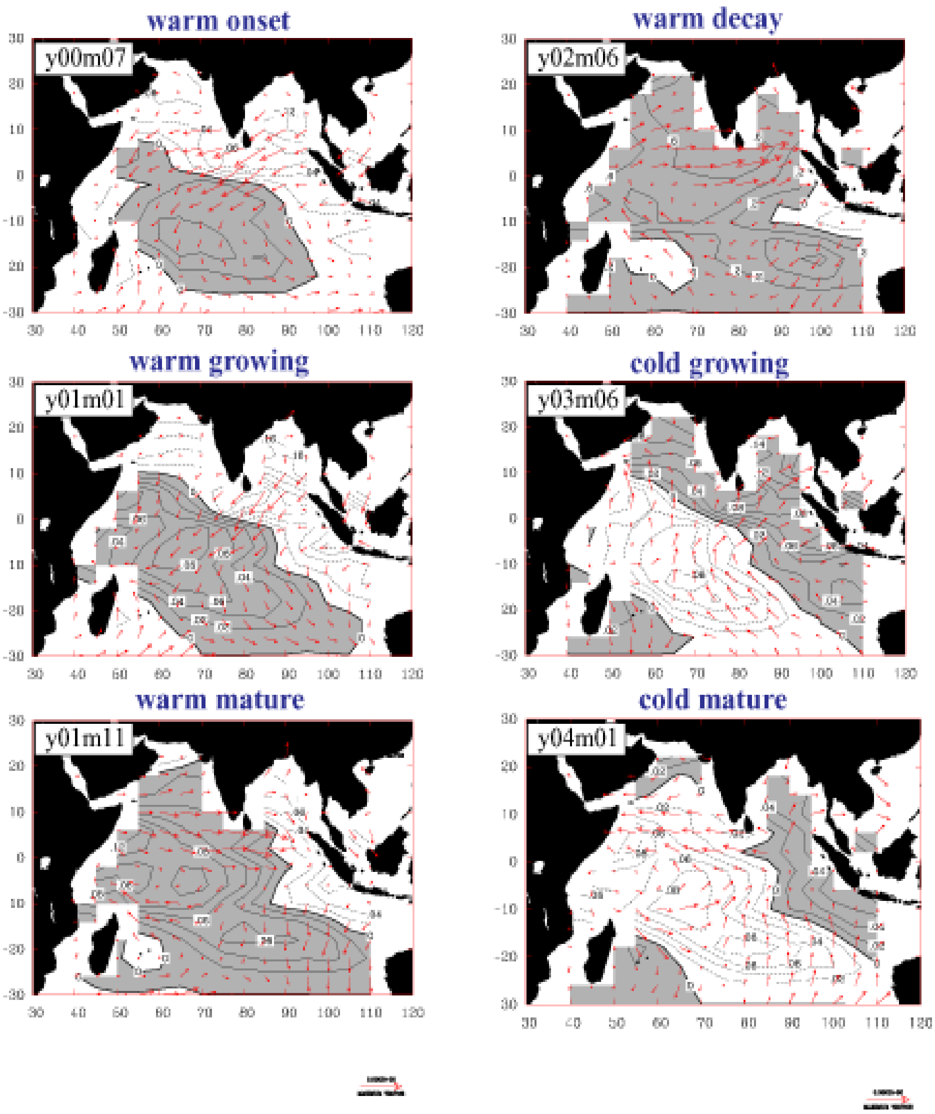

Fig. 3 The evolution of the IOZM in the coupled UCLA model showing the growth and decay phases and association with monsoon wind forcing. (From Yu and Lau, 2004). Units of wind is in ms^{-1} and SST in ^{o}C.

5. Land Surface Processes

Land surface processes influence the monsoon by changing surface temperatures and the overlying atmospheric circulation. The soil moisture and albedo effects associated with snow, and snow melt in the preceding winter and spring change the surface temperatures and affects the subsequent evolution of the monsoon (Barnett *et al.* 1989; Yasunari *et al.* 1991). More snow leads to larger albedo, which reflects more radiation to the space and reduces energy absorption by the earth. More snow also leads to larger snowmelt, which cools the land surface. Elevated land surface such the Tibetan Plateau is often covered by snow in cold seasons and its role in the Asian monsoon has been well documented (Luo and Yanai 1984; He *et al.* 1987; and Li and Yanai 1996).

Yang and Lau (1998) have found that the impact of snow and soil moisture on the Asian monsoon mainly occurs over tropical lands and coastal water domains, and that land surface processes mainly influence the monsoon in May and June, but less significantly during July-September. In addition, compared to SST, land surface process exerts a relatively weaker influence on the tropical Asian monsoon. This is consistent with the result obtained by Koster and Suarez (1995) and Xue *et al.* (1996) who found that over relatively wet (dry) areas, SST (land surface process) affects the climate more significantly.

While the land surface forcing may be smaller in scale, it can amplify or reduce an existing wind or precipitation anomaly driven by large-scale SST anomalies. Land surface processes impact the monsoon through altering the regional water and energy cycles (Lau and Bua, 1998). As shown in the left-land portion of Fig. 4, an initial increase in precipitation will lead to increased soil moisture, which enhances evaporation, moistens and destabilizes the atmospheric boundary layer and promotes the growth of atmospheric convection and precipitation. The associated release of latent heat warms the troposphere, and leads to low-level moisture convergence, which further enhances precipitation. An increase in evaporation cools the land surface directly, as indicated in the NF1 link in Fig. 4. Increased in highly reflected clouds due to increased convection will further contribute to the cooling of the land surface, by reducing solar radiation reaching the earth surface. The surface cooling will reduce the thermal contrast between land and ocean and therefore weaken the monsoon flow, reducing the moisture supply, hence reduces rainfall, as shown by the NF2 link in the center of Fig. 4.

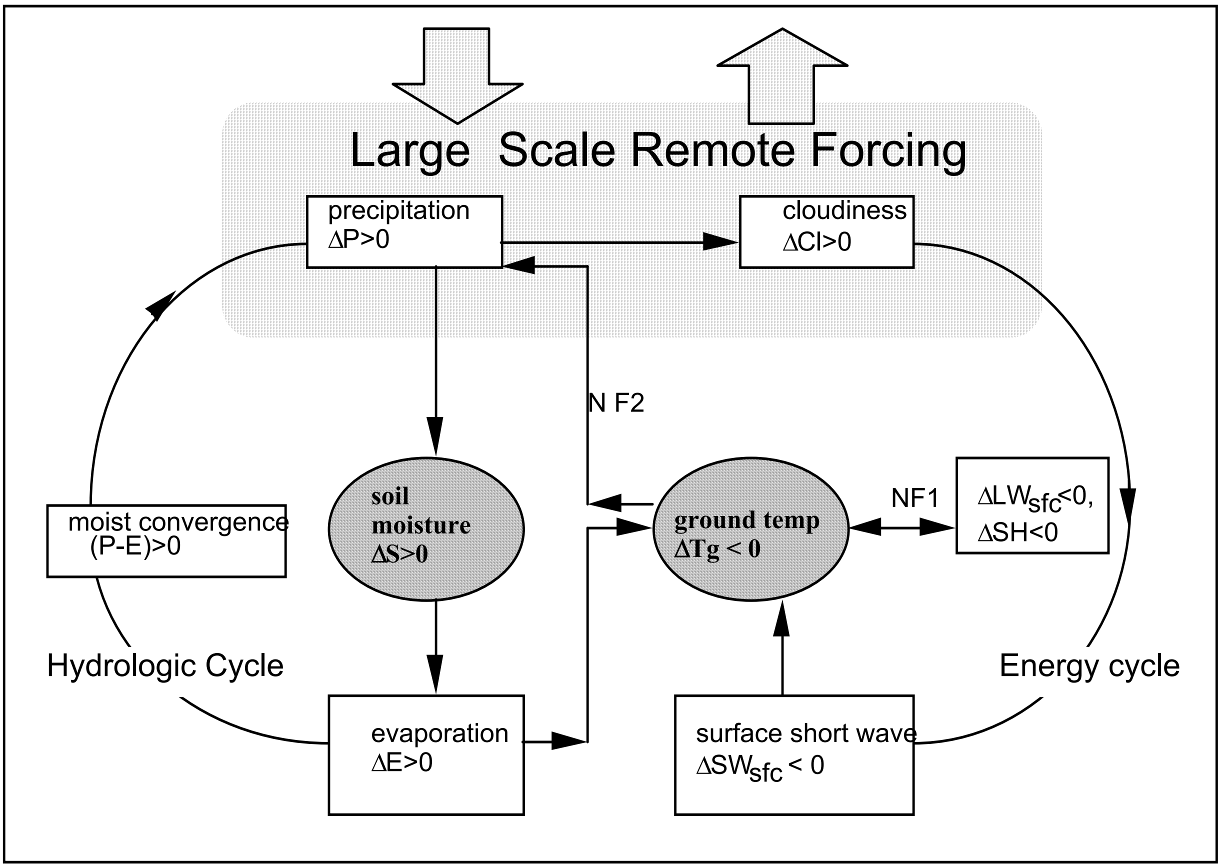

Fig. 4 Schematic diagram showing the fast response and feedback processes in the water and energy cycle in monsoon land regions, induced by slowly varying forcing of the atmosphere-land region. (from Lau and Bua 1998).

6. Tropospheric Biennial Oscillation

The TBO represents one of the most prominent IAV of the Asian and Australian monsoons. Many studies have shown that the variability of monsoon precipitation and circulation exhibits strong signals of quasi-biennial oscillation (e.g., Mooley and Parthasarathy 1984; Meehl 1987; Lau and Sheu 1988; Yasunari 1990; Ropelewski *et al.* 1992; Shen and Lau 1995; Webster *et al.* 1998; Li *et al.* 2001a). TBO signals are found not only in the variability of summer rainfall over Asia but also in the relationship between the Asian monsoon and other climate phenomena such as ENSO (Shukla and Paolino 1983; Yasunari 1990; Lau and Yang 1996, Meehl 1997, Meehl and Arblaster 2002a,b, Meehl *et al.* 2003).

Fig. 5 shows an idealized sequence of the major features of the TBO. Starting from DJF (Fig.5a) of a weak Australian monsoon, above normal SST appears in the Indian Ocean and the central-eastern Pacific Ocean, while below normal SST is found to the north of Australia. The SST distribution and overlying circulation cells resemble those associated with the warm phase of El Nino. The Eurasian continent is warmer and has less snow, in connection with the establishment of an anomalous high pressure ridge that signals an atmospheric Rossby wave response to tropical heating. In the following MAM (Fig.5b), the key features in the coupled ocean-atmosphere-land system persist because of the memories in SST and associated thermocline. In JJA, the warmest SST anomalies shift eastward over the equatorial western Pacific and the eastern Indian Ocean, where the thermocline deepens, and the coupled system enters the La Nina phase. As a consequence, the summer monsoon rainfall increases over South Asia, signaling a stronger Indian monsoon. The western Indian Ocean begins to cool because of stronger westerly wind monsoon wind forcing. The summertime features are largely maintained through the following SON (Fig. 5d), with increased convection over the maritime continent, and the cooling over the Indian Ocean expanded eastward. The land surfaces over South Asia and subtropical Eurasia also begin to cool due to saturated soil moisture from the previous wetter-than-normal summer season. The enhanced convection over the maritime continent suppresses convection over the Indian Ocean, and migrates eastward in concert with the annual cycle of convection over northern Australian, ushering in a stronger Australian monsoon in the following DJF. In the western Pacific, the SST reaches its maximum, and the thermocline starts to shoal, while the Indian Ocean cooling is most extensive. The increased convection over northern Australia and weak convection over the Indian Ocean provide forcing to a Rossby wave response characterized by an anomalous trough and a colder, more snow-covered subtropical Eurasia. Note that in about the time interval of one year, the signs of the anomalies in monsoon coupled ocean-atmosphere-land system have completely reversed. The cycle is repeated in the next twelve months with the opposite polarities completing a full biennial cycle. In this scenario, the TBO is strongly tied to the relaxing time scale of the thermocline in the western Pacific and the Indian Ocean, and is phase-locked to the annual cycles of SST and convection in the Indo-Pacific region.

Recently, there have been a number of theories proposed for the mechanisms and reasons for prominent two-year time scale of the TBO. Goswami (1995) suggested that interaction of monsoon dynamics and the annual cycle of convection is sufficient to induce a monsoon TBO. Chang and Li (2000), and Li et al (2001) emphasized on the role of the Indian Ocean, and its interaction with the transition from the South Asia to the Australia monsoon. Kim and Lau (2000) suggested that the TBO represent an intrinsic interaction between monsoon processes via the seasonal variations of intraseasonal forcing and ENSO dynamics.

Certain aspects of the TBO and its interaction with ENSO have been simulated by coupling AGCMs to simple ocean mixed-layer models. For instance, Lau and Nath (2000), Lau *et al.* (2004) and Lau and Wang (2005) have examined the evolution of the atmospheric and SST conditions during imposed ENSO cycles in such systems. They have shown that the `direct' atmospheric response to ENSO forcing leads to weakened monsoons over South and East Asia during the year of the warm episodes. Through the `atmospheric bridge' mechanism, the reduced wind speeds and cloud cover result in increased SST over the Arabian Sea, Bay of Bengal, and the South and East China Seas. This oceanic warming is seen to persist for several seasons through positive air-sea feedbacks, and the enhanced supply of moisture is conducive to a stronger monsoon in the following year. This chain of simulated events indicate that the interaction of ENSO and seasonal anomalies could contribute to the biennial tendency of the monsoon system by modulating the coupled atmosphere-ocean environment in the Indo-western Pacific region.

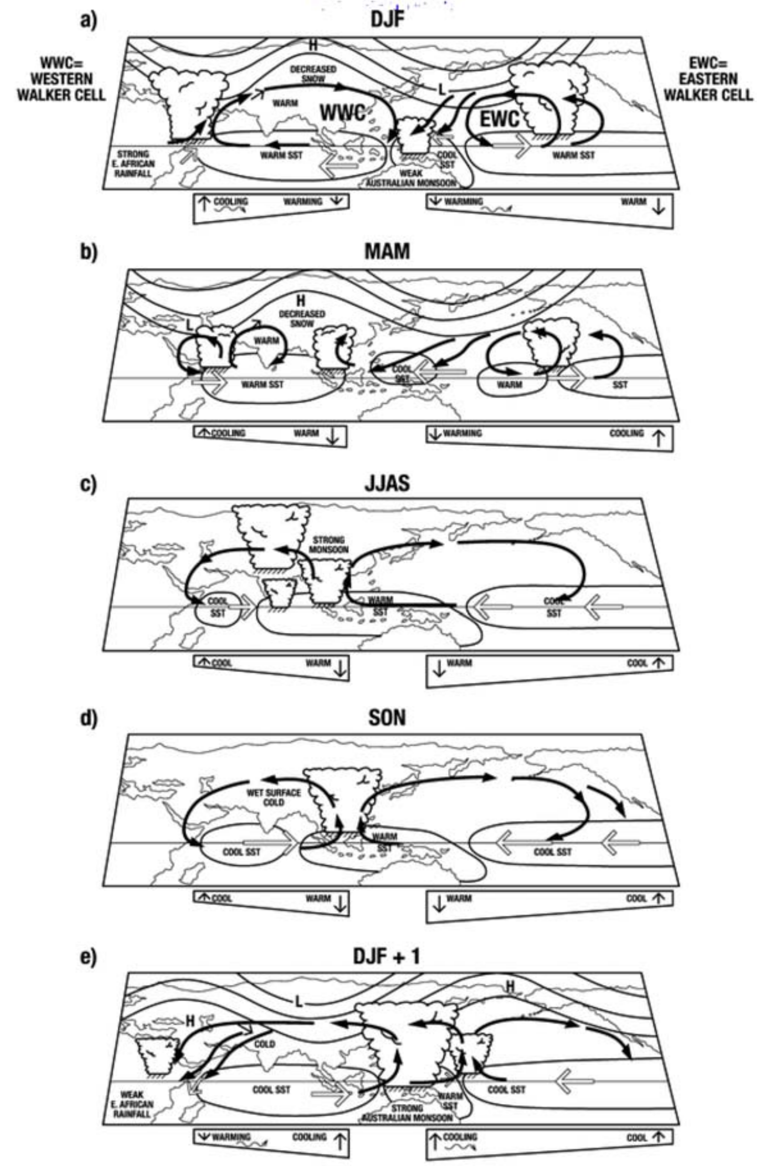

Fig. 5 Schemaitcs illustrating key anomalies of convection, SST, surface winds, Walker circulation, extratropical circulation, land surface changes and thermocline tendencies in the Indian Ocean and the western Pacific associated with the TBO. (From Meehl and Arblaster 2002).

7. Global Teleconnection

The interaction of monsoon with ENSO through the Walker Circulation and associated Rossby wave response is a prime example of global teleconnection associated with the IAV of Asian monsoon. However the Asian monsoon may generate telconnection and interacts with components of the global circulation through additional pathways. A number of recent studies have shown that the Asian monsoon may interact with components of the global circulation through the East Asian jet stream in ways that are distinct from ENSO. Yang *et al.* (2002) find a relationship between the winter climate in East Asia and North America through the variability of the East Asian westerly jet stream. They found that changes in surface temperature and precipitation in the two regions can be explained by fluctuations of the jet stream and associated stationary wave patterns. When the jet stream is strong, cold and dry climate appears in East Asia, while precipitation is generally suppressed over North America, and surface temperatures drops in the east, but rises in the west. When the jet stream is above normal, more wave energy is transported from the source over East Asia to the sink over North America, via the North Pacific, as evidence in the pattern of horizontal and vertical stationary wave fluxes (Fig. 6).

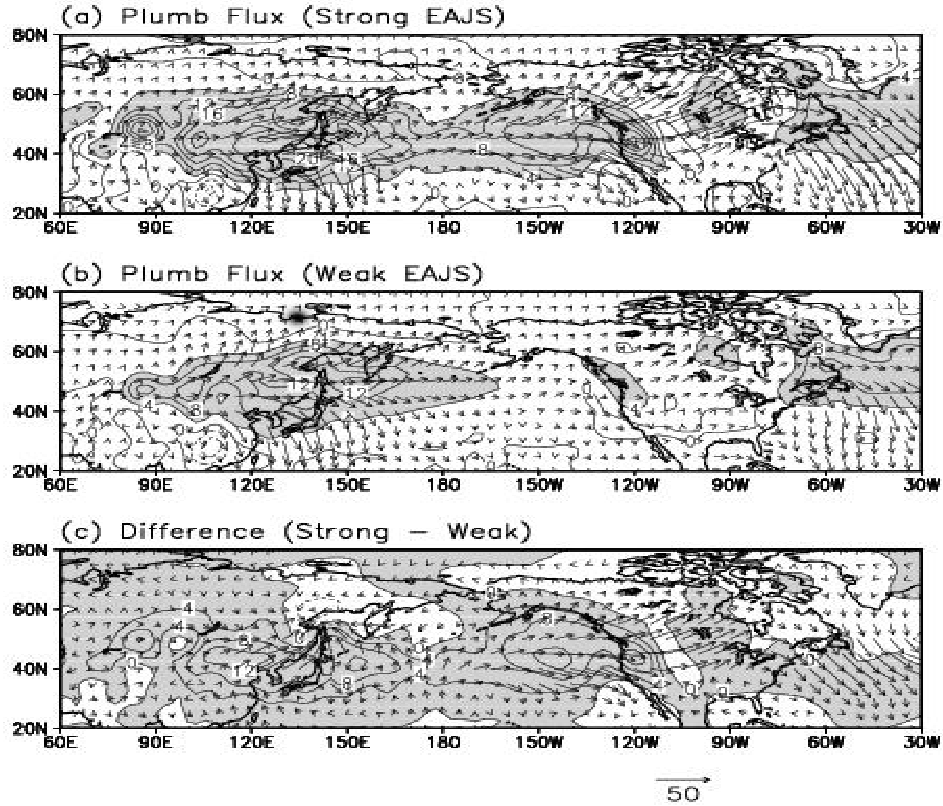

Fig. 6 DJF stationary wave activity flux for (a) strong East Asian jet stream, (b) weak Jet stream and (c) strong minus weak jet streams. The vectors (m^2s^{-2}) and contours (x 10^4 m^2s^{-2}) represent the horizontal component at 300 mb and vertical component at 850 mb. Values large than 4 x 104 m^2s^{-2} are shaded. (From Yang *et al.* 2002).

Recently, Lau and Weng (2002) and Lau *et al.* (2004a, b) find summertime teleconnection patterns linking rainfall and temperature anomalies over East Asia and North America. Two summertime teleconnection patterns have been identified. The first one, referred to by the authors as the “Tokyo-Chicago Express”, consists of a large-scale coherent structure of zonally oriented winds and geopoential, and SST anomalies over the North Pacific, linking rainfall anomalies over Japan and northeastern China to anomalies of the same sign over western Canada, the northern Great Plains and the Mid-west of the United States. This mode has a significant correlation with Nino-3 SST during the April, but appears as a coupled ocean-atmosphere mode over the North Pacific in JJA (Lau *et al.* 2004a). The second mode referred as the “Shanghai-Kansas Express” features Rossby wavetrain signal in 500 mb geopotential emanating from central East Asia across the North Pacific to North America

(Fig. 7a). This mode is uncorrelated with ENSO, and is likely spawned by fluctuations of heat sources and sinks in the Indo-Pacific monsoon region, as evidence in the 200 mb divergence center over the Indian Ocean (Fig. 7b). The possible role of a low-latitude monsoon heat source/sink for this mode is also consistent with the coexistence of similar and even stronger wave pattern in the South Hemisphere. The dynamical mechanisms of these summertime teleconnection modes, and their interactions with the extratropical oceans and lands are still unknown, and are clearly an important subject of future monsoon research.

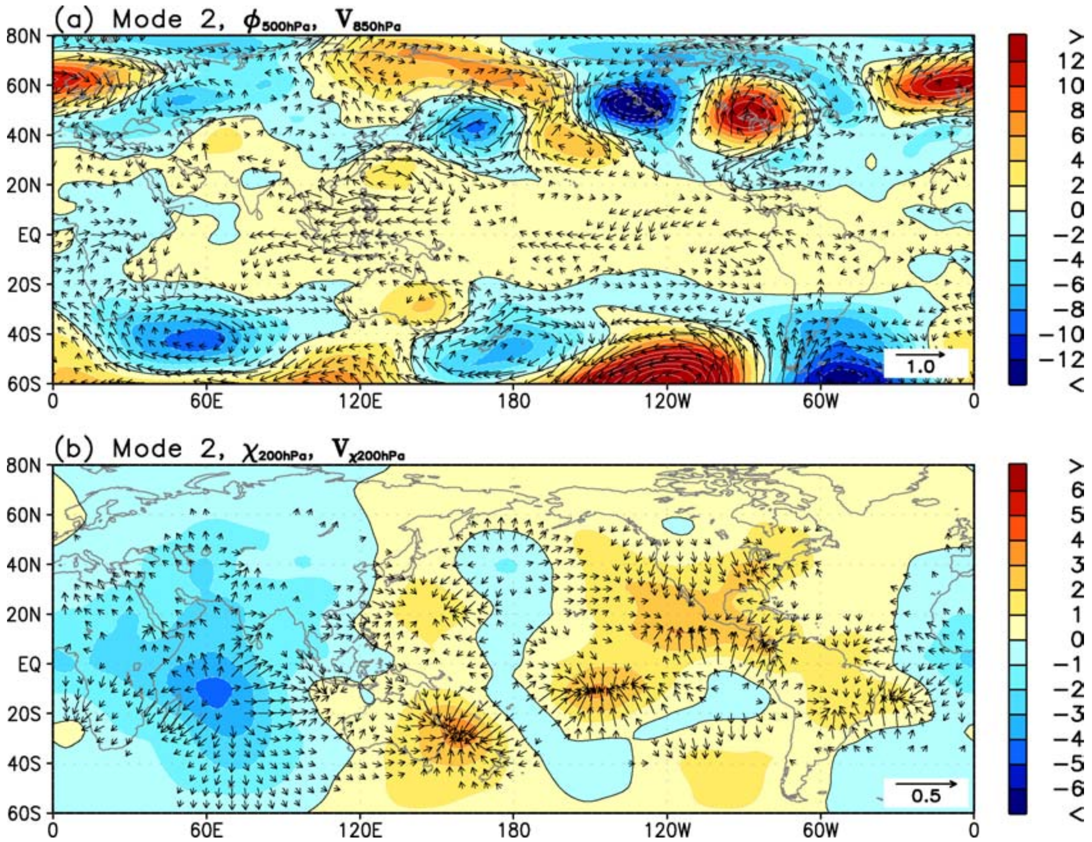

Fig. 7. Regression of the principal component of the second mode of North America summer rainfall against (a) 500-mb geopotential height and 850-mb winds and (b) 200-mb velocity potential and divergent winds. (From Lau *et al.* 2003).

Some facets of the observed teleconnections between variability of the East Asian monsoon and temperature/precipitation over North America have been reproduced in AGCM runs analyzed by Lau *et al.* (2005). The experimental setup entails the simulation of atmospheric responses to prescribed SST anomalies in the Indo-western Pacific sector, which have been generated by remote forcing from ENSO via the 'atmospheric bridge' mechanism. The model results indicate that such anomalous SST forcing produces midlatitude atmospheric signals in both hemispheres during the boreal summer season following the ENSO events. These signals are characterized by a strong degree of zonal symmetry, and are attributable to both extratropical eddy-mean flow interactions and to forcing by tropical diabatic heating. Of particular interest is the extension of the anomalous atmospheric features from East Asia across the North Pacific to the North American sector, where the accompanying precipitation and surface temperature anomalies are reminiscent of prolonged summertime droughts and heat regions observed in that region.

8. Effects of Aerosols

Evidence is now emerging that increased loading of anthropogenic aerosols, and natural aerosols from dust storms over northwestern Asia, Middle East and North Africa may have strong impacts on IAV of the Asian monsoon (Ramanathan, 2000, Menon *et al.* 2001). The ways in which aerosols affect heating in the atmosphere and the earth surface are complex and strongly dependent on the aerosol types, concentration, vertical and horizontal distribution, the ambient circulation regime, and the surface albedo. Sulfate aerosols efficiently scatter, while carbonaceous aerosols e.g., black carbon and organic aerosols strongly absorb shortwave radiation. Therefore while aerosols of all types will reduce solar radiation reaching the earth surface inducing surface cooling, different aerosols will lead to differential heating/cooling in the atmosphere and the surface and alters the vertical moist stability and convective potential of the atmosphere. In the monsoon region, sulfate and carbonaceous aerosols from industrial pollution and biomass burning, as well as dust storm from spring, in areas within and adjacent to the monsoon regions, may alters the land-sea distribution, excite global teleconnection signals, which pre-conditions the large-scale circulation and atmosphere-land-ocean boundary conditions altering the subsequent evolution of the monsoon (Kim *et al.* 2004).

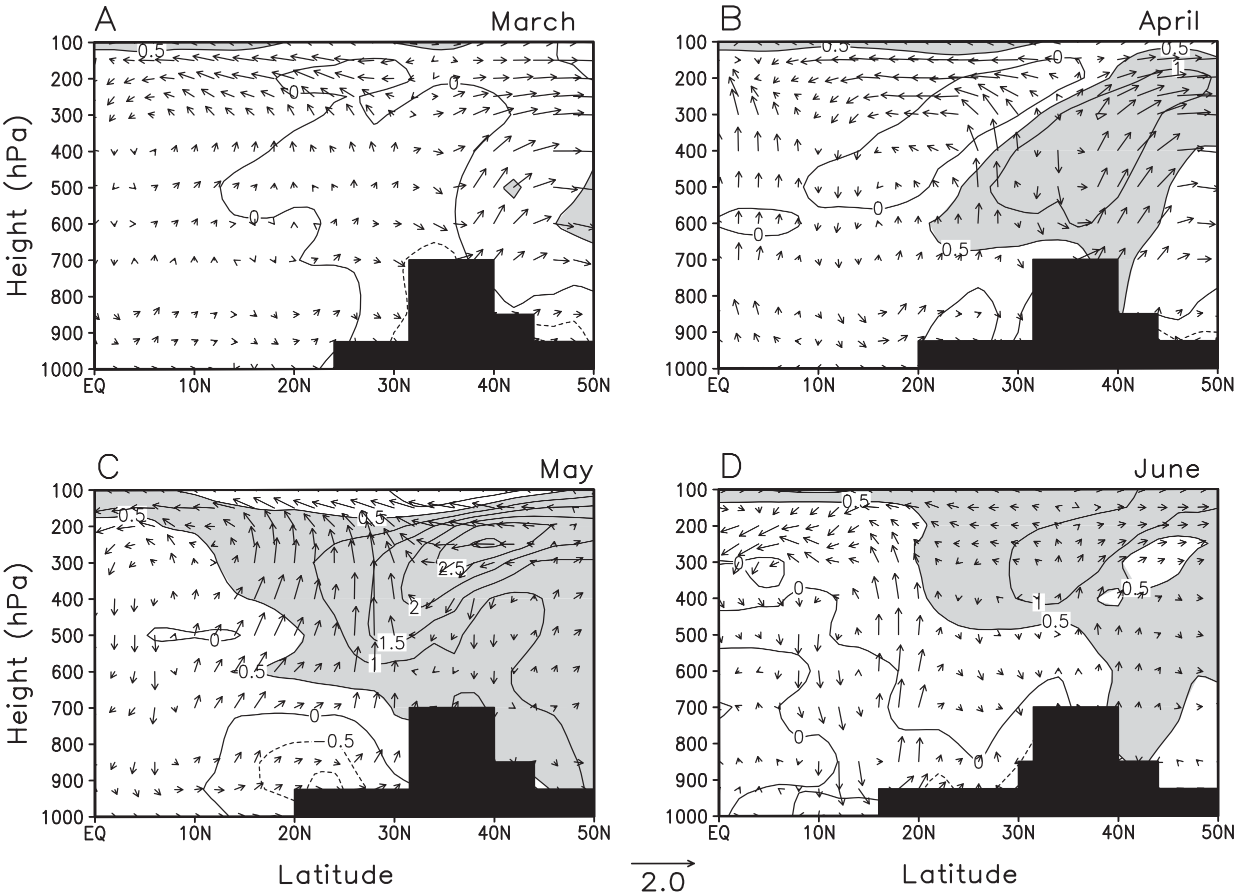

Fig. 8 Latitude-height distributions of temperature and meridional circulation anomalies induced by the presence of aerosols for (a) March, (b) April, (c) May, and (d) June over latitude belts of 80-100°E. Units of pressure velocity and meridional wind are -10^{-4} hPa s^{-1} and m s^{-1}, respectively. Contour intervals are 0.5°C. (From Lau and Kim 2004)

In a recent GCM experiment making of realistic distribution of global aerosols sources and distribution from chemistry transport models, Lau and Kim (2004) shows that absorbing aerosols, i.e., black carbon and dust, induce large-scale upper-level heating anomaly over the Tibetan Plateau in April and May, ushering in an early onset of the Indian summer monsoon. Absorbing aerosols also enhance lower-level heating and anomalous ascent over northern India, intensifying the Indian monsoon. Fig. 8 shows the evolution of upper tropospheric warming and induced vertical motions by absorbing aerosols from March to June, over Tibetan Plateau due to effects of aerosols. While intensifying the Indian monsoon, overall, the aerosol-induced large-scale surface temperature cooling leads to a reduction of monsoon rainfall over the East Asia continent, and adjacent oceanic regions.

The study of aerosol forcing inducing radiative and dynamical feedback on global water cycle and climate variability of the monsoon regions is now only in its embryonic stage. At present, the forcing functions are just beginning to be known and estimated from satellite observations and from global aerosols transport models, which are un-coupled to global climate models. Moreover, model physics in climate models are ill-equipped to explore the full interactions of aerosol forcing with the cloud and precipitation microphysics, including the direct and indirect effects. Improving model physics of clouds, precipitation, and boundary layer processes in climate models are paramount in moving forward aerosol- climate research. Thus far aerosol effects have not attracted much attention in the monsoon research community. Aerosol-climate interaction may fill a gap in understanding the linkage of monsoon climate variability to global change, and should be a top priority in future monsoon climate research.

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